PROPERTIES OF AUDITORY TEMPORAL INTEGRATION REVEALED BY MISMATCH NEGATIVITY

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Abstract— **The mismatch negativity (MMN), a component of event–related potentials (ERP), was recorded to investigate the properties of the storage of auditory temporal sequences in the sensory memory. First, the MMN elicited by the infrequent change in a pair of closely spaced tones was evaluated. In ignored condition, it was shown that the MMN was elicited only when the total duration of the tone pair was less than 400ms. However in attended condition, MMN was also elicited when the duration was 500ms. This result showed that the function of "temporal integration", which integrated the short time history by using a time window, existed in sensory memory, and its maximum period was between 300ms–400ms, but this period could be prolonged by the attention process. Second, the relationship between temporal configuration of tone sequence and elicited MMN was evaluated. Temporal configuration was changed by inserting additional tones between the two tones in the tone pair. From this experiment, it was suggested that the performance of auditory sensory memory was influenced by the temporal configuration of the tone sequence to be stored, as well as its total duration. These results may help to approach the neuronal mechanism of auditory scene analysis.**

Keywords— **Mismatch negativity (MMN), sensory memory, audition, temporal sequence, temporal integration, attention**

I. Introduction

Auditory sensory memory is thought to have an important role for flexible processing in central auditory system, as the transient ("buffer") memory storage of incoming temporal sequence. In the sensory memory, there exists a function of temporal integration, which integrates successive information into some entities [1], [2], [3], which is required for the perception of auditory events [4]. But the period of the time window for temporal integration, and the relation to the temporal configuration (structure) of the stored temporal information are still remained unclear.

Such properties of auditory sensory memory can be observed by recording the mismatch negativity (MMN), which is one of the event–related potential (ERP) components. MMN is elicited when some of the frequent ("standard") stimuli are randomly replaced by the infrequent ("deviant") stimuli with some different attributes to the standard ones (oddball paradigm). MMN is believed to be the measure of pre–attentive sensory memory properties and is quite related to the auditory discrimination and storage functions [5], [6].

In this article, some experimental results on auditory sensory memory to store tone sequence were shown. It was shown that the period of temporal window of integration was 300–400ms, and the attention could prolong the period of temporal window of integration, and that the MMN activities with attention had more complex distributions on frontal area than in ignored condition. It was also shown the storage capacity of auditory sensory memory might be related to the temporal configuration (structure) of stored tone sequence. These results may be a help to approach neuronal mechanism of auditory scene analysis [4].

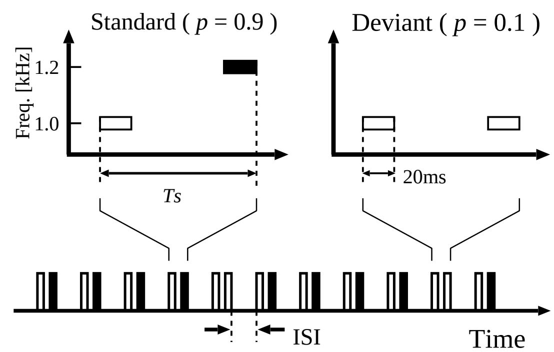

Fig. 1. Schematic diagram of stimulus train used in Experiment 1. Each stimulus consisted of a pair of tone bursts. Only the frequency of the second tone was different between standard and deviant stimuli.

II. Experiment 1: Width of Time Window

In Experiment 1, the relationship between the total stimulus duration and the magnitude of elicited MMN was investigated to evaluate the period of time window of integration.

A. Methods

Four subjects with normal hearing were studied in an electromagnetically shielded room. Auditory stimuli were delivered to the left ear by headphone. Each subject was required to read a self–selected book and was instructed to ignore the presented auditory stimuli (reading condition).

Fig.1 shows the stimulation tone sequence in this experiment. Each stimulus consisted of two tones, each of which was 20ms, 60dB SL tone bursts (rise/fall time was 5ms). Frequencies of the first and second tones were 1.0kHz, 1.2kHz (standard stimulus, $p = 0.9$), 1.0kHz, 1.0kHz (deviant stimulus, $p = 0.1$) respectively, i.e. the deviance between standard and deviant stimulus was only the frequency of the second tone.

Inter–stimulus interval (ISI) was set to 700ms. The stimulus duration (T_s) was fixed to 100, 200, 300 and 400ms within each session, and the relationship of T_s to elicited MMN was observed.

The EEG was recorded with Ag–AgCl electrodes from four channels (Fz, Cz, F3, F4). The vertical electro–oculogram (EOG) was also recorded from the outer canthus of the left eye. Two electrodes attached on A1 and A2 were short–circuited and took them as the reference.

EEG was recorded with a bandpass filter setting of 0.1–100Hz and analyzed from 100ms before the onset of the first tone to 600ms after the offset of the second tone (sampling rate 1000Hz). EEG epochs in which recorded amplitudes exceeded $\pm 100\mu$V were automatically rejected. The accepted EEG epochs were averaged.

For the evaluation of MMN magnitude, the amplitude

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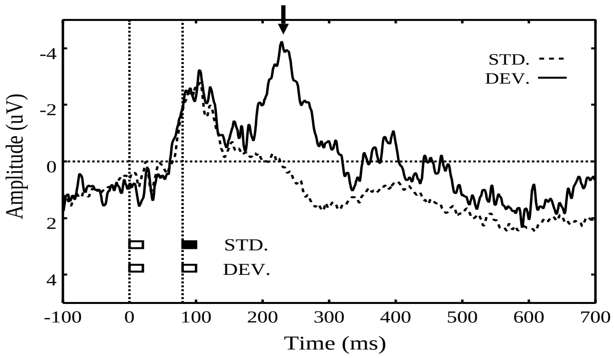
(a) $T_s = 100$ms



(b) $T_s = 400$ms

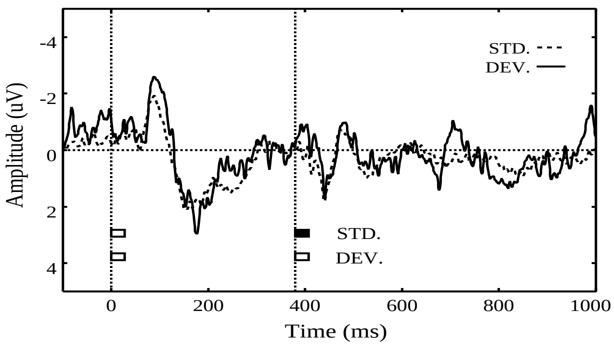


Fig. 2. [Experiment 1] Averaged standard (dashed) and deviant (solid) waveforms of one subject. (a) $T_s = 100$ms. (b) $T_s = 400$ms.

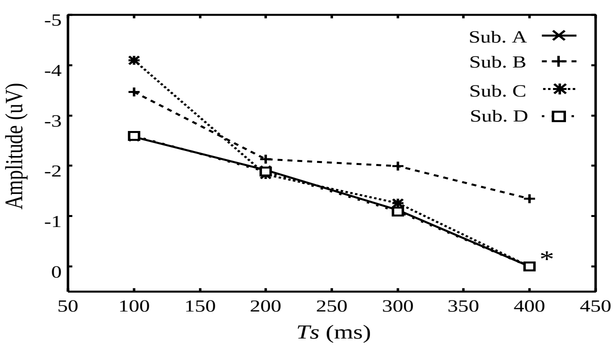


Fig. 3. [Experiment 1] Relationship between stimulus duration (T_s) and amplitude of observed MMN component for all subjects (taken from F4). On Subjects A, C and D, no significant MMN was observed on $T_s = 400$ms (marked *).

of the negative peak in the difference waveform (deviant − standard) whose latency was 100–250ms from the onset of the deviated tone was analyzed after the application of lowpass filter (30Hz) to the averaged waveform. The data were statistically analyzed using one–way analysis of variance (ANOVA) for repeated measures with factors stimulus type (standard and deviant, $p < 0.05$).

B. Results

Fig.2 shows the examples of averaged response for standard and deviant stimuli, taken from F4. When the stimulus duration (T_s) was 100ms, clear MMN could be observed (Fig.2(a)). But in this subject, no significant MMN component was appeared when $T_s = 400$ms.

The peak amplitudes of the observed MMN for all subjects are shown in Fig.3. This result indicated that the longer T_s, the smaller the magnitude of MMN. In this experiment, the only deviance was the frequency of the second tone. So if the two tones were processed independently from one another, such dependency on T_s would not be observed. Thus this result might indicate that the two tones were processed as a unitary event, i.e. the temporal integration mechanism existed in auditory sensory memory.

Moreover, MMN was disappeared for three subjects when $T_s = 400$ms (Subjects A, C and D, marked * in Fig.3). This showed the time window of integration could be 300 − 400ms in ignored condition.

III. Experiment 2: Attention Effect

Attention effect for the longer tone sequence, for which no MMN could be observed on ignored oddball task was studied.

A. Methods

Two subjects with normal hearing were studied in an electromagnetically shielded room. Auditory stimuli were delivered to the left ear by headphone. This experiment was done both in ignored (read self–selected book) and attended (count the number of deviant stimuli) condition.

In this experiment, the number of deviant stimuli in a single session was three. Frequencies of the first and the second tones were 1.0kHz, 1.2kHz (standard stimulus, $p = 0.85$), 1.0kHz, 1.0kHz (deviant stimulus 1, $p = 0.05$), 1.2kHz, 1.0kHz (deviant stimulus 2, $p = 0.05$), 1.2kHz, 1.2kHz (deviant stimulus 3, $p = 0.05$), respectively. ISI was set to 700ms, and T_s was fixed to 100 and 500ms within each session. Note that MMN was not elicited when $T_s = 400$ms in Experiment 1.

In this experiment, 32 channel whole head EEG signals based on extended international 10–20 system, including vertical and horizontal EOG channels, were recorded. Details were the same as in Experiment 1.

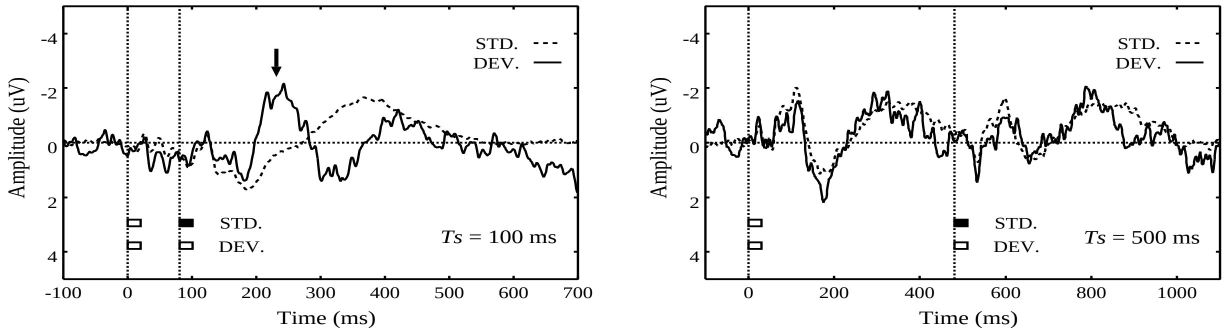
B. Results

Fig.4 shows the averaged waveforms for standard and deviant 1 (deviance on the second tone) of one subject for both ignored and attended condition. In each condition, maximum amplitude of MMN was recorded from F4. In ignored condition, MMN was elicited only when $T_s = 100$ms (Fig.4(a)). This result followed the result in Experiment 1. However in attended condition, MMN was observed when $T_s = 500$ms, as well as 100ms (Fig.4(b)). This result showed that the attention prolonged the temporal window of integration on auditory sensory memory.

The scalp distributions of the observed MMN (shown by arrows in Fig.4) on the same subject are depicted in Fig.5. It was found that the MMN activities in attended condition (Fig.5(b), (c)) had more complex distributions on frontal area than in ignored condition (Fig.5(a)).

Though MMN is elicited both in ignored and attended condition, MMN in attended condition may include additional subcomponents from that in ignored condition [7]. Source localization and investigation on relation to the attention and working memory system [8] were left for the further study.

(a) Ignored



(b) Attended

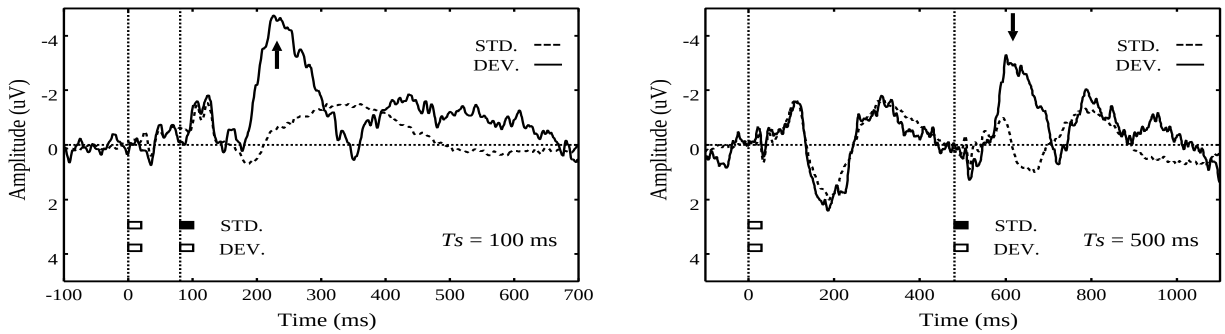


Fig. 4. [Experiment 2] Averaged standard (dashed) and deviant (solid) waveforms for T_s = 100ms (left) and T_s = 500ms (right). Taken from F4 of one subject. (a) Ignored condition. (b) Attended condition.

(a) (b) (c)

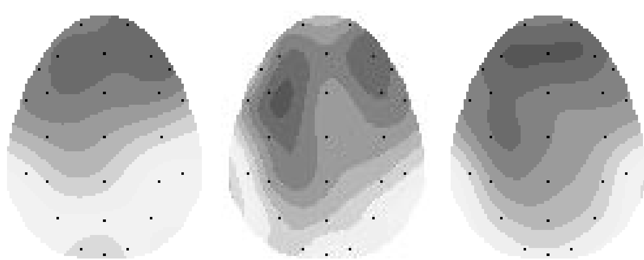


Fig. 5. [Experiment 2] Scalp distribution of the observed MMN. Scales were from -5μV (black) to 5μV (white). (a) T_s = 100ms, ignored. (b) T_s = 100ms, attended. (c) T_s = 500ms, attended.

IV. Experiment 3: Temporal Configuration of Tone Sequence

In Experiment 3, the relationship between capacity of auditory sensory memory and temporal configuration (structure) of the stored tone sequence as reflected by MMN was evaluated.

A. Methods

Temporal configurations of the presented tone sequence are shown in Fig.6. Each sequence consisted of the first tone (open box), inserted tone (black box) and the last tone (gray box). All tones were 1kHz, 60dB SL tone bursts (rise/fall time was 5ms) on standard stimulus ($p = 0.9$), and only the frequency of the last tone was replaced by 2kHz on deviant stimulus ($p = 0.1$). The durations of the first and the last tone were fixed to 40ms.

In this experiment, temporal structure of the stimulus was controlled by changing the property of the inserted tone by the following three ways. Experiment 3(a): number of 20ms inserted tones (0, 1, 2, 3), Experiment 3(b): duration of an inserted tone (20ms, 40ms, 60ms), Experiment 3(c): serial position of an inserted tone: interval from offset of the first tone to onset of inserted tone (20ms (Early), 50ms (Center), 80ms (Late)). The intervals in a tone sequence were same in Experiment 3(a) and 3(b).

The number of subjects were five (Experiment 3(a)) and three (Experiment 3(b) and 3(c)). In Experiment 3(a), two additional experiments were done for two subjects (Subjects A and B). Detailed procedure was the same as in Experiment 1.

B. Results

The amplitude of the observed MMN on each experiment is depicted in Fig.7. In Experiment 3(a), MMN amplitude was reduced when the number of inserted tones was increased on four subjects (Fig.7(a)). In Experiment 3(b), MMN amplitude was the smallest when the duration of inserted tone was 60ms for all subjects (Fig.7(b)). And on two subjects, the largest MMN amplitude was observed for the duration 40ms. And in Experiment 3(c), MMN amplitude was reduced when the inserted tone was shifted to the last tone on two subjects (Fig.7(c)).

These results suggested that the temporal configuration of the stored tone sequence (complexity of tone sequence, ratio between the total periods of tones and intervals in a tone sequence, and temporal pattern of tone sequence), as well as the total duration of the tone sequence, affected the performance of the auditory sensory memory. Detailed investigations were left for the further study.

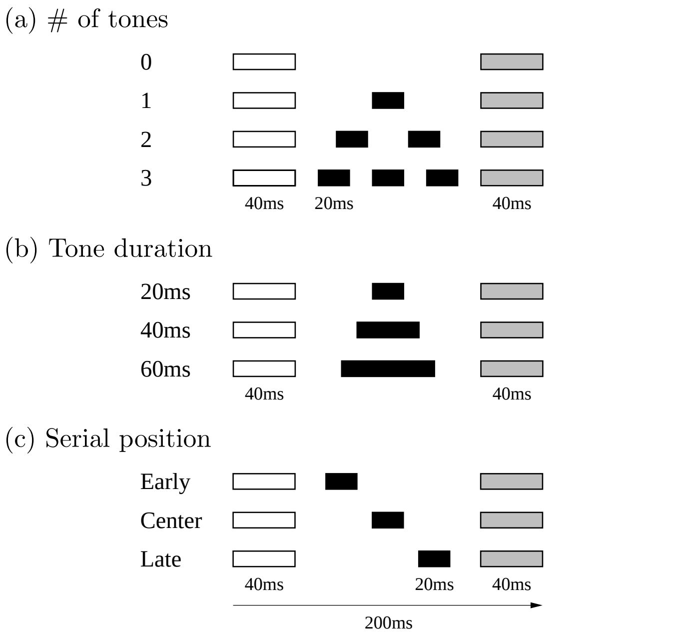


Fig. 6. Tone sequence configuration presented to subjects in Experiment 3. On standard stimulus, first (open box), inserted (black box) and last (gray box) tones were 1kHz tone bursts, and frequency of last tone was replaced to 2kHz on deviant stimulus. The effect of change in (a) the number of inserted tones (Experiment 3(a)), duration of an inserted tone (Experiment 3(b)), (c) serial position of an inserted tone (Experiment 3(c)), were investigated.

V. Conclusions

Some properties of auditory sensory memory to store temporal information were shown. In Experiment 1, the relationship between the temporal integration and the duration of stored temporal sequence in ignored condition was examined. It was shown that the period of temporal window of integration was 300–400ms. In Experiment 2, the attention effect for the storage in auditory sensory memory was investigated. It was found that the attention could prolong the duration of temporal window of integration, and that the MMN activities with attention had more complex distributions on frontal area than in ignored condition. And in Experiment 3, the influence of temporal configuration of stored tone sequence to the MMN magnitude was observed. From this experiment, it was shown the storage capacity of auditory sensory memory might be related to the temporal structure of stored tone sequence. These findings might lead to uncover the nature of temporal grouping of auditory temporal stimuli.

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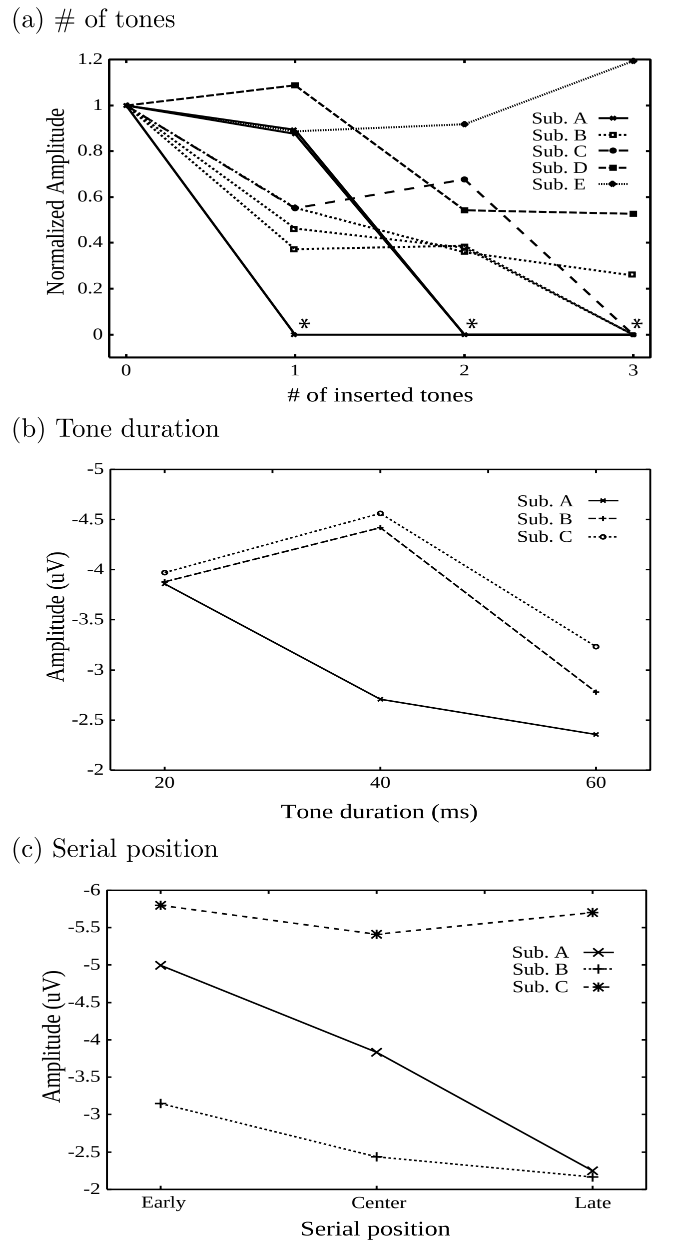

Fig. 7. [Experiment 3] MMN amplitude dependencies to a change in temporal configuration of presented tone stimulus (taken from Fz). (a)The number of inserted tones, (b) duration of an inserted tone, (c) serial position of an inserted tone. MMN amplitude was normalized by that for single inserted tone in (a). No significant MMN was observed on the data marked *.

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